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AN UNUSUAL BROAD LINE PROFILE IN THE QSO 0054+144—EVIDENCE FOR AN OPTICAL JET?

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ABSTRACT

Narrow components in the profiles of the broad Balmer and Mg II emission lines were observed in the QSO 0054+144 (PHL 909). The redshift given by the narrow permitted lines is smaller than that of the narrow forbidden [O III] lines, by an amount corresponding to a velocity difference of ~ 1000 km s^{-1}. There was a possible change in both the broad and narrow permitted lines between 1980 and 1986. We suggest that the narrow Balmer component may have been produced in a short-lived jetlike structure moving outward from the center of the QSO with this relative line-of-sight velocity.

Subject heading: quasars

I. INTRODUCTION

The broad emission line regions (BELRs) in QSOs and active galaxies are believed to consist of a number of clouds with electron densities $N_e \sim 10^{9-10}$ cm^{-3}, moving with velocities of up to several thousand km s^{-1}. Various models have been proposed for the form of the velocity field as well as the range of physical properties (see Ferland and Shields 1985). While most broad emission line profiles in QSO spectra are smooth, in some cases narrow components exist in the permitted line profiles and can be clearly distinguished from the strong, broad components (Osterbrock, Koski, and Phillips 1975). The narrow cores of permitted lines usually are at the same redshifts as the narrow forbidden lines such as [O III] λ5007, indicating that they are probably formed in the lower density narrow-line region that occupies a large volume and extends to a greater distance from the central energy source than the radius within which BELR clouds lie.

In several Seyfert galaxies, sharp peaks have been seen in the Balmer lines, with redshifts different from those of the centers of the broad Balmer line profiles. In the radio galaxy 3C 227 narrow peaks with a redshift of $z = 0.0877$ were observed in the Balmer lines (Osterbrock, Koski, and Phillips 1976), and this redshift was larger by $+0.007$ than that of the center of the broad Balmer line profiles. On the other hand, Osterbrock and Shuder (1982) found the narrow Balmer components that were blueshifted with respect to the broad lines in Mrk 876.

We have been investigating a sample of QSOs for line intensity variability (Zheng and Burbidge 1986; Zheng *et al.* 1987; Zheng 1988), and have obtained recent spectrophotometric data on the QSO 0054+144 (PHL 909) for which we had data taken 6 yr earlier. This object has a redshift $z = 0.171$ (Schmidt 1974) and is a strong X-ray source (Zamorani *et al.* 1981). It is one of the QSO samples studied by Bradley (1985) in an investigation of correlations between optical and X-ray properties. The Hβ profile is so unusual among more than 100 low-redshift QSOs that we have studied, and this prompted us to obtain new observations as part of the search for line variability. Although shifted broad lines have been reported extensively (e.g., Gaskell 1983; Peterson, Korista, and Cota 1987), a displaced narrow peak in the QSO's spectrum is still rarely found.

II. OBSERVATIONS

All the observations discussed here were made with the image-tube image-dissector spectrograph on the 3 m Shane telescope at Lick Observatory. Gratings of 600 line mm^{-1} were used, giving a resolution of ~ 9 Å. Scans of 32 minutes each, for the wavelengths of 3100–5100 Å, 4900–7500 Å, and 6900–8700 Å, were made on 1980 August 12, November 9, and September 5, respectively. Each scan was accompanied by a large-aperture scan for flux calibration by comparison with standard stars. Wavelength calibrations have been checked by using night-sky lines, and we believe the wavelengths are accurate to ± 1 Å.

Figure 1 shows the composite spectrum obtained from the sum of the three 1980 observations. It is very similar to Figure 2 of Bradley (1985), which included additional data taken in 1981. The Hβ line is very broad and cannot be approximated with a logarithmic curve. As in the Seyfert galaxies mentioned in § I, the line has a narrow component which does not connect smoothly with the broad component.

Two 32-minute scans, covering wavelengths 3100–5200 Å and 4000–6200 Å, were obtained in 1986 July, using the same instrument at the Lick 3 m telescope. These did not have accompanying large-aperture scans, therefore the fluxes have been normalized by the usual method (see Tohline and Osterbrock 1976) in which it is assumed that [O III] λ5007, produced throughout a large volume, has constant flux over a period long compared to the time scale of our observations. Because of the unusual Hβ profile, a deconvolution using Gaussian profiles or Hα profile did not work well. Therefore, the flux of [O III] λ4959 was assumed to be one-third that of the [O III] λ5007 and then was removed from the broad Hβ flux. As a result, the errors in flux for the broad and narrow Hβ in the 1980 data are estimated as 20% and 30%, respectively, as determined from different possible fits. The wavelengths, however, are checked, by night-sky lines and are estimated to be accurate within 1 Å.

III. RESULTS AND DISCUSSION

From the 1980 data shown in Figure 1, we have measured redshifts, intensities, and full widths at zero intensity (FWZI) of both narrow and broad components; these are listed in Table

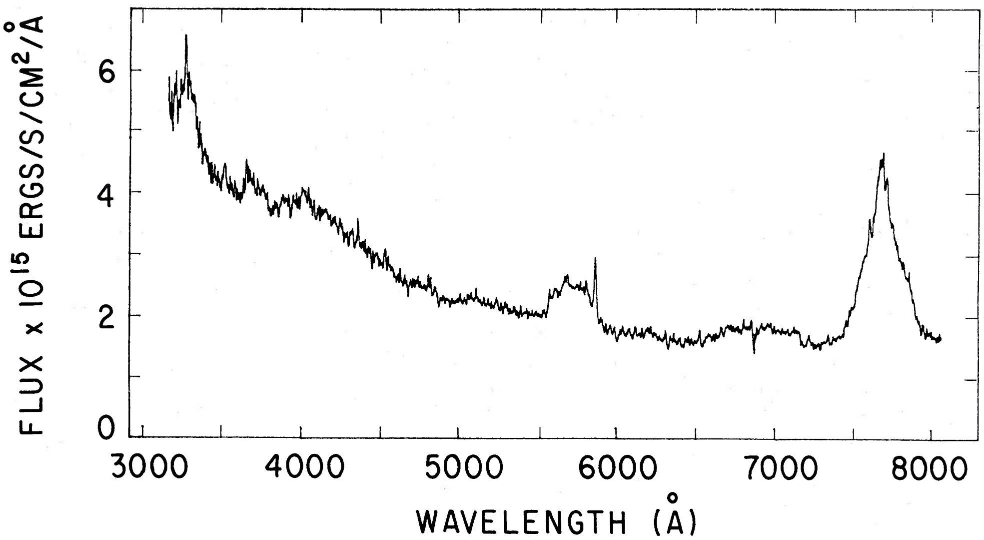

FIG. 1.—Spectrum of the QSO 0054+154 taken in 1980

1, where both the line fluxes and the widths are corrected to zero redshift. Note that Mg II λ2798 has a sharp peak whose redshift agrees with that of the narrow component in Hβ, but this line lies so close to the atmospheric cutoff, and the edge of our scans, that measurement of its broad component is very uncertain.

The narrow Hβ component is blueshifted with respect to the narrow [O III] λ5007 line by 0.003, corresponding to $\sim$1000 km s^{-1}. Since these narrow features have well-determined wavelengths, we believe the wavelength shift of $\sim$14 Å producing this redshift difference is significant and well outside the measurement errors.

We have not attempted to measure the structure in the Hα profile because of strong atmospheric absorption (the A band) within its profile. The removal of this feature by dividing the spectrum by that of a standard star is only partially successful, although the total intensity of the Hα broad line should be reasonably accurate.

The comparison of the 1980 and 1986 spectrum between 5100 and 6000 Å plotted in Figure 2 shows a significant change in both the Hβ and Hγ profiles despite a higher noise level in the 1986 data. The extended high-intensity wings of Hβ observed in 1980, which gave the broad component its flat-

TABLE 1

EMISSION LINE MEASUREMENT

Line	Redshift	Intensity	FWZI (Å)
	Narrow		
[O III] 5007	0.1712	14	28
Hβ	0.1682	3.6	33
		(:1)	33
Mg II 2798	0.1680	7.8	17:
		(:2)	
	Broad		
Hα	0.1711:	550	453
Hβ	0.1740:	115	250
		(66:)	(235:)
Hγ	0.1730:	<12	175:
		(12:)	(132:)
Mg II 2798	0.1675:	110:	163
		(55:)	(145)

NOTE.—Results are from 1980 data. The 1986 measurements are presented in parentheses with fluxes calibrated by the [O III] intensity. Line intensity is in units of 10^{-14} ergs cm^{-2} s^{-1}. All fluxes and widths are corrected to zero redshift. A colon denotes large uncertainty of more than 30% and 0.25% for line fluxes and redshift, respectively.

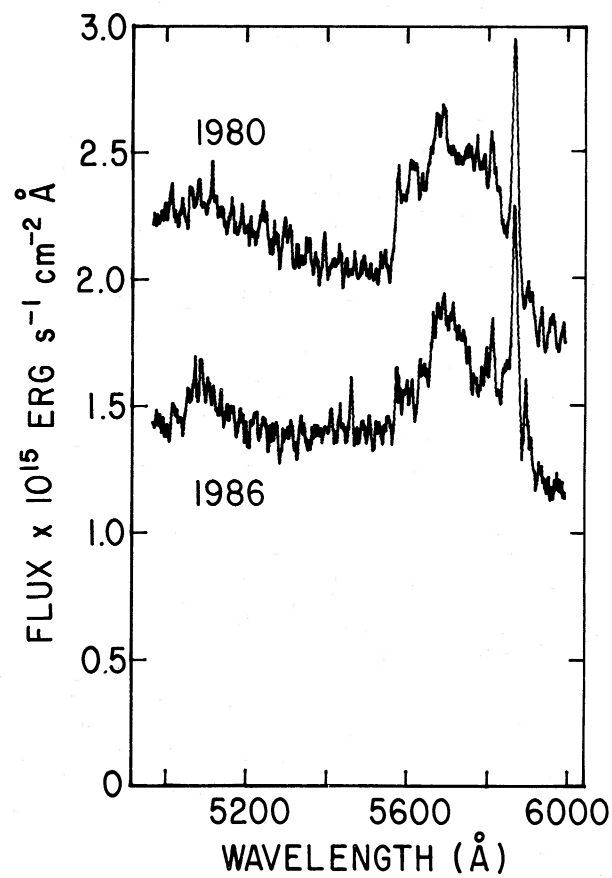

FIG. 2.—Change in Hβ line profile. The flux scale is for 1980 values and the 1986 flux level is normalized by the intensity of [O III] λ5007.

topped shape, have decreased to the extent that [O III] λ4959 is clearly separated from Hβ in 1986. The narrow Hβ component was not so clearly seen. The fluxes plotted in Figure 2 have been normalized as usual by taking the flux in [O III] λ5007 to be constant, and they show that the continuum level measured at 5500 Å had decreased by ~30% between 1980 and 1986. The 1986 measures of intensity and FWHM are given in Table 1 in parentheses, under the 1980 values. The FWZI of Hβ has decreased from 215 Å in 1980 to 100 Å in 1986, and that of Hγ decreased in a similar manner. The total intensity of Hβ decreased by a factor of nearly 2; only an upper limit on the intensity of the Hγ can be set in 1980 because of the great width of the line, but the 1986 value should be accurate to 15%. The Hβ line should receive no sizable contribution from the narrow-line region, otherwise another narrow Hβ peak would have been present.

Limited by the quality of 1986 data, the line variation of Hβ components can only be considered as qualitative. However, the profile change of broad Hβ is obvious, especially in its wings. This change is unlikely to be due to the presence of Fe II features. The optical Fe II is not pronounced in this object. According to Grandi (1981), the observed mean blend ratio of Fe II λ4570/λλ5190, 5320 is about unity. In this object the intensity of Fe II λ4570 is measured to be less than 10% of that of the Hβ. Therefore we conclude that the significant change in the Hβ line is not due to contamination by other lines. The narrow component in Mg II λ2798, like that of Hβ, was not clearly seen in 1986, and the upper limits to both their intensities are given in parentheses in Table 1.

The redshift difference of the narrow components of permitted lines with respect to forbidden lines implies that they are probably not formed in the same region. The probable time development of the narrow Hβ feature indicates that they may be formed in the broad-line region. We consider some possible explanations for the line structure and variations that have been discussed previously, especially in Seyfert galaxies.

1. Supermassive binary system. Following a theoretical possibility proposed by Begelman, Blandford, and Rees (1980), Gaskell (1983) suggested that the displaced peaks of permitted lines may result from the orbital velocity of a binary system. A recent report by Peterson, Korista, and Cota (1987) supports the assumption for existence of such binary system in the Seyfert galaxy NGC 5548. The broad features they determined have full line widths of ~3000 km s^{-1}, significantly broader than that reported in this paper.

2. Obscuration. Capriotti, Foltz, and Byard (1979) suggested that asymmetrical profiles may be produced from a system of clouds with considerable opacity. Like the model of a binary system, this explanation will generally apply only to broad features because of the effect of bulk velocity dispersion.

3. Variability and time-delay effect. Capriotti, Foltz, and Peterson (1982) studied the light-echo effect on spikes in broad-line profiles. Such an effect has a strong time dependence on the scale of light-crossing time of the whole BELR. Since a typical time scale is less than 1 lt-yr for QSOs while the narrow feature in 0054+154 was observed for at least 3 yr, it is unlikely that this effect would account for the observed narrow feature in this object.

4. Optical jet. Ulrich *et al.* (1985) reported two spikes near the C IV line in the Seyfert galaxy NGC 4151. These narrow features varied in intensity by a factor of 3 in 10 days. They suggested that the emitting region is associated with a two-sided jet. If the jet can maintain a small ejection angle, the resultant spike may in fact be quite narrow. Peterson (1987) has also discussed the possibility that a blueshifted line emission may arise in gas ejected from the central object.

We suggest that the velocity difference, the profile, and the time scale for variation can be explained by the presence of a short-lived jet that formed and emerged from the BELR at an outflow velocity of ~1000 km s^{-1}. The total volume producing the narrow permitted line can be roughly estimated, based on a photoionization calculation. The volume can be expressed as

$$V = \frac{4\pi f_{\mathrm{H}\beta} z^2 c^2}{\alpha_{\mathrm{H}\beta} N_e^{\,2} \mathrm{H}_0^{\,2} \epsilon} ,$$

where $f_{\mathrm{H}\beta}$, $\alpha_{\mathrm{H}\beta}$, and ϵ are the flux and the total recombination coefficient for Hβ, and the photon energy of Hβ, respectively. With the Hubble constant $H_0 = 55$ km s^{-1} Mpc^{-1}, electron density $N_e = 3 \times 10^{11}$ cm^{-3}, and a temperature of 10^4 K, the whole volume producing the narrow Hβ emission should be of the order of 3×10^{44} cm^3. Furthermore, if the column density is assumed to be 10^{22} cm^{-2}, then the jet should span an illuminated area of ~10^{34} cm^2. At a distance of 0.5 lt-yr from the central energy source, a value roughly derived from line variations for BELRs in other low-redshift QSOs (Zheng 1986), this represents an angle of approximately 6° with respect to the central source, a reasonable value for a narrow jet. The total mass of emitting gas can therefore be estimated as 0.1 $M_\odot$. The presence of narrow Mg II λ2798 is an indication that this feature is formed in the same region as the narrow Hβ. Therefore, the cloud or jet may be optically thick to the Lyman-edge photons.

The profile of Hβ is considerably different from that of Hα. The velocity dispersion of Hα is 40% larger than that of Hβ, as determined at their FWZIs. But their line widths at 70% intensity are 215 and 225 Å, respectively. This indicates that the Hβ line is broader than Hα by 40% at this part of the profile. Since the observed line fluxes are the grand sum of emission from different regions in which the physical parameters vary significantly, it is reasonable to assume that the Hβ line receives contributions, especially to its wings, from a region where the Hβ/Hα ratio is exceptionally large. In addition, it is noted that the Hβ/Hγ ratio is at least 10 and is larger than that in other QSOs of low redshift which we have studied. Such a steep Balmer decrement is not in agreement with conventional line-emission calculations. Therefore, the unusual line shape and line ratios may imply that part of the BELR arises under very special physical conditions which have not been well understood.

There may be a physical relation between the blueshifted narrow component and the shape of broad permitted lines. If the observed redshift difference is attributed to radiation-driven outflow velocity, then the derived radial velocity, only ~1000 km s^{-1}, indicates that the jet is formed near the central source and has not been accelerated to high radial velocity. On the other hand, the bulk velocity of the whole BELR is ~10^4 km s^{-1}, as determined from the line width of the broad permitted-line components. This flat, broad emission feature may originate from a shell-like structure in the outer BELR which moves at higher velocity. Since this narrow component has no smooth connection with other emission profiles, there is probably a lack of clouds in the inner BELR so that this narrow component is prominent. Otherwise, a smooth but clear peak should be observed as in many other cases. This can also explain why the broad component of Hβ does not have a clear peak at its center point.

If the velocity field is a radiation-driven outflow, then the innermost part would contribute mostly to the line center, hence a flat profile can result from a shell-shaped BELR. According to Capriotti, Foltz, and Byard (1980), the line profile produced in a region in which the velocity is between $u_{\rm min}$ and $u_{\rm max}$ is

$$L_\nu = \text{const} \int_a^{u_{\rm max}} \frac{dv}{v} ,$$

where a is $u_{\rm min}$ or $|\lambda - \lambda_0| c/\lambda_0$, whichever is larger.

In such a case, the line profile would be flat between

$$\lambda_0\left(1 - \frac{u_{\rm min}}{c}\right) \quad \text{and} \quad \lambda_0\left(1 + \frac{u_{\rm min}}{c}\right) .$$

For a very thin shell, the resulting profile would be a rectangle, indicating the lack of emitting gas contributing to the line center. Between

$$\lambda_0\left(1 - \frac{u_{\rm min}}{c}\right) \quad \text{and} \quad \lambda_0\left(1 - \frac{u_{\rm max}}{c}\right) ,$$

and between

$$\lambda_0\left(1 + \frac{u_{\rm min}}{c}\right) \quad \text{and} \quad \lambda_0\left(1 + \frac{u_{\rm max}}{c}\right) ,$$

the profile would be a part of the logarithmic curve. So the velocity field would consist of the sum of two contributions, producing a composite profile in which the flat rectangular part comes from the inner BELR and the wings from the logarithmic profile.

An alternative explanation for the flat and broad Hβ profile is that it could be produced by a gravitationally bound BELR. For the optically thin case, the radial component of the orbital motion is so strong that the resulting profile is broad and flat. This assumption gains support from the observed fact that the change in broad Hβ occurs near its wings. In such a case, the inner BELR, with a larger orbital velocity, would contribute mostly to the line wings, and a line variation would be most likely to occur in this part. A similar time evolution of broad line profiles was reported in Seyfert galaxies (Ulrich 1984).

In summary, the displaced narrow permitted lines suggest that not all narrow lines are produced in a distant low-density region. Some narrow lines may be formed in a small volume in the BELR and may change in a period of several years. Such an emitting volume may be in the form of a jet which moves away from the central source and gradually merges into the surrounding BELR.

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